STATUS OF THE CARBON DIOXIDE MISCIBLE FLOODING METHOD OF ENHANCED OIL RECOVERY IN THE UNITED STATES

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INTRODUCTION

In 1978, oil accounted for approximately half of all United States energy needs (2). During that same year, 6.9 billion barrels of petroleum were consumed by the United States. Slightly over half, or 3.75 billion barrels, were produced domestically; the rest (3.15 billion barrels) was imported (2). Since then, United States production of oil has decreased along with demand. However, our dependence on foreign oil is still very great (Figure 1).

Three major steps are being taken to reduce this dependence on foreign oil. New sources of oil and energy are being developed. The processing of "oil" shales and tar sands are just two examples of new sources of energy that have the potential to decrease our dependence on foreign oil. However, the problems associated with these "new" sources of energy may inhibit them from contributing a great deal to the United States energy supply in the near future. Exploration and development of new domestic oil supplies can also reduce dependence on foreign oil. New reservoirs of oil are constantly being discovered, especially in the western states, in Alaska, and on the Outer Continental Shelf. Along with developing unconventional sources of energy and developing new domestic oil supplies, a third step is being taken to decrease the United States foreign oil dependence. More efficient methods of recovering oil from known fields are being developed.

Three hundred billion barrels of oil. Although it is hard to imagine that this much oil still lies in existing reser-

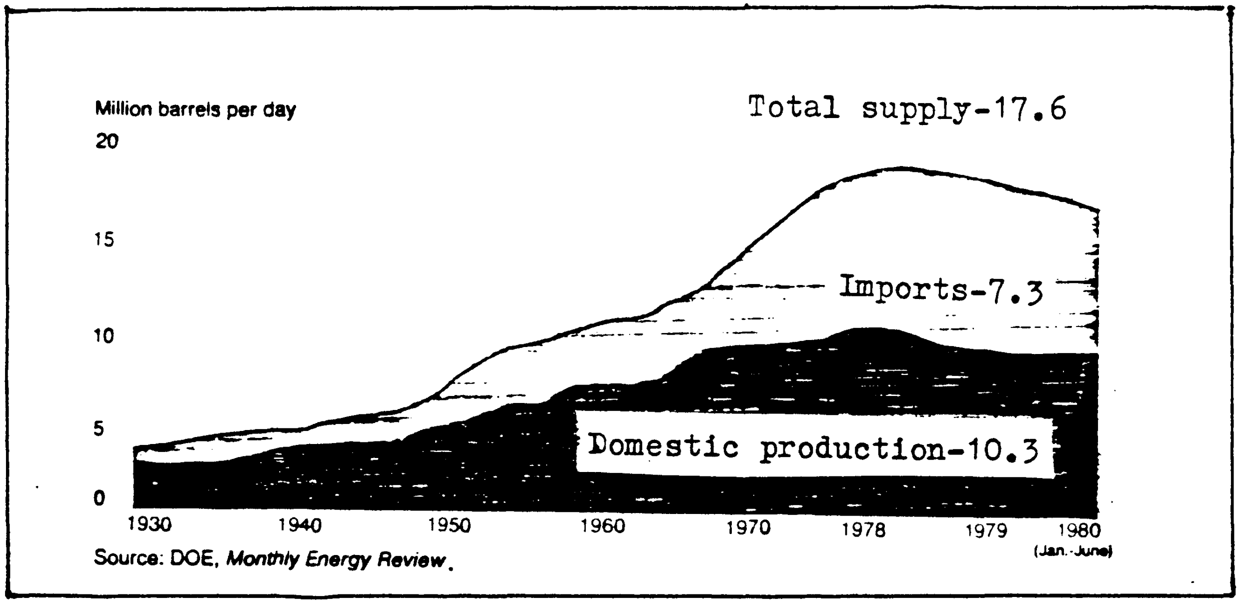

Figure 1. United States petroleum supply--1930-1980

(Modified from pamphlet on energy, Gulf Oil Corporation, January 1981) voirs in the U.S., it is even more amazing that only another 10% of it can be recovered by conventional techniques (11). Recovery from individual reservoirs by conventional methods ranges from as low as 5% to as high as 80% of the original oil in place (4). This broad range of recovery efficiencies is due to the fact that not two oil reservoirs are exactly alike. Each oil reservoir has a specific set of physical and chemical characteristics. The average recovery of oil from reservoirs in the United States, by conventional methods is only 35% (4). Often most of the oil is left in the ground after conventional recovery methods have been completed. Since the average oil recovery by conventional methods is 35%, this means that at many oil fields, recovery is even less.

Methods of recovering oil from reservoirs that conventional techniques leave behind are known as Enhanced Oil Recovery (EOR) methods, and have their greatest potential at these "below average recovery" reservoirs. EOR techniques are commonly adopted at oil fields where conventional primary and secondary recovery methods can no longer produce oil economically. Primary recovery methods utilize the reservoir's inherent forces, such as expansion of the oil or associated gas, water pressure, or gravity to free trapped oil. Gradually, as oil is produced, these natural forces diminish and a secondary recovery method may be initiated. Secondary recovery methods involve pumping fluids into the reservoir in order to sustain or restore the reservoir's natural pressure and to prolong production. Waterflooding is the term given to a secondary recovery method that uses water as the injected fluid.

Waterflooding currently accounts for half of the U.S. daily oil production (4). The oil that remains in reservoirs after waterflooding, which is in most cases more than half of the original amount of oil in place, is the broad target for EOR techniques and is estimated at 270 billion barrels in the United States alone (11). Even if only a small portion of this is produced by EOR techniques, it would add significantly to the U.S. oil supply, decrease our dependence on foreign oil, and thereby strengthen our national security.

METHODS OF ENHANCED OIL RECOVERY

Miscible Recovery

Gas injection into an oil reservoir is not a new technology. In the 1950's, hydrocarbon gas, such as methane or propane, was pumped into oil reservoirs in order to delay the pressure decline, eliminate interfaces and capillary forces, and ultimately improve recovery (9). This method is now known as hydrocarbon miscible flooding andis used on a limited scale today. Two of the major reasons for limited use of this method is the cost and availability of hydrocarbon gas. It is expensive andis often in short supply. Another problem with this method of oil recovery is that one valuable natural resource (natural gas) is being consumed to produce another (petroleum). Despite these problems, in some areas of high pressure and high temperature reservoirs, hydrocarbon miscible flooding is the most economical method of improved oil recovery.

Chemical Recovery

Several other forms of enhanced oil recovery exist. For example, chemicals, such as polymers or surfactants (detergents), are sometimes injected into a reservoir to increase recovery of oil. These chemicals can be added to water in order to increase the water's viscosity. This "thick water" when injected, then has a greater ability to displace oil, however this improved waterflooding process increases recovery only slightly. In addition, there are few suitable reservoirs, therefore, polymer flooding is expected to have only limited applications in the future.

Surfactant flooding is another type of "chemical" oil recovery method that also has limited use. At present, the problems associated with this method are greater than the benefits. The surfactants, when injected, tend to cling to rock grain surfaces, resulting in a large loss of injected fluid (9). Pumping detergent into the ground isn't a great idea anyway. This method seems to be more of an underground pollution problem rather than an oil recovery method.

Thermal Recovery

A third group of enhanced oil recovery techniques uses heat. With these thermal methods, heat is applied to the reservoir and therefore to the oil, which causes theoil to become less viscous and to flow more easily. Hot water injection was first used but this did not contain enough heat energy to thin out the more viscous oils. Steam, which has the energy needed to decrease the viscosity of oil in reservoirs, has been used for over 20 years as an EOR technique, and will continue to be used in certain regions, suchas California, where there are heavy or thick oil reservoirs. Thermally enhanced oil recovery is the most common EOR technique and accounts for about 80% of all EOR projects in the U.S. (5). An inherent drawback of these thermal EOR methods is the fact that some of the oil recovered has to be used to produce steam.

THE CARBON DIOXIDE MISCIBLE FLOODING METHOD

Description

One method of miscible oil recovery that has great potential is carbon dioxide (CO_2) miscible flooding. When CO_2 is injected into an oil reservoir, the pressure will increase. At a critical pressure, the oil or hydrocarbons that come in contact with the CO_2 will mix with the CO_2. As more CO_2 is injected, three distinct compositional zones are created in the oil reservoir. The first zone is composed of pure CO_2 and extends from the injection well out to the leading edge of CO_2. Since CO_2 is soluable in oil, a second zone is created which is composed of a mixture of CO_2 and hydrocarbons. The third zone is simply the oil-saturated rock of the reservoir. As the CO_2 comes in contact with oil, it mixes with the oil, making the oil less viscous and easier to flow (4). As additional fluid is injected, this "mixed" zone is forced away from injection wells toward producing wells where a CO_2-rich crude is produced (Figure 2). Producing and injection wells can be arranged in many ways depending

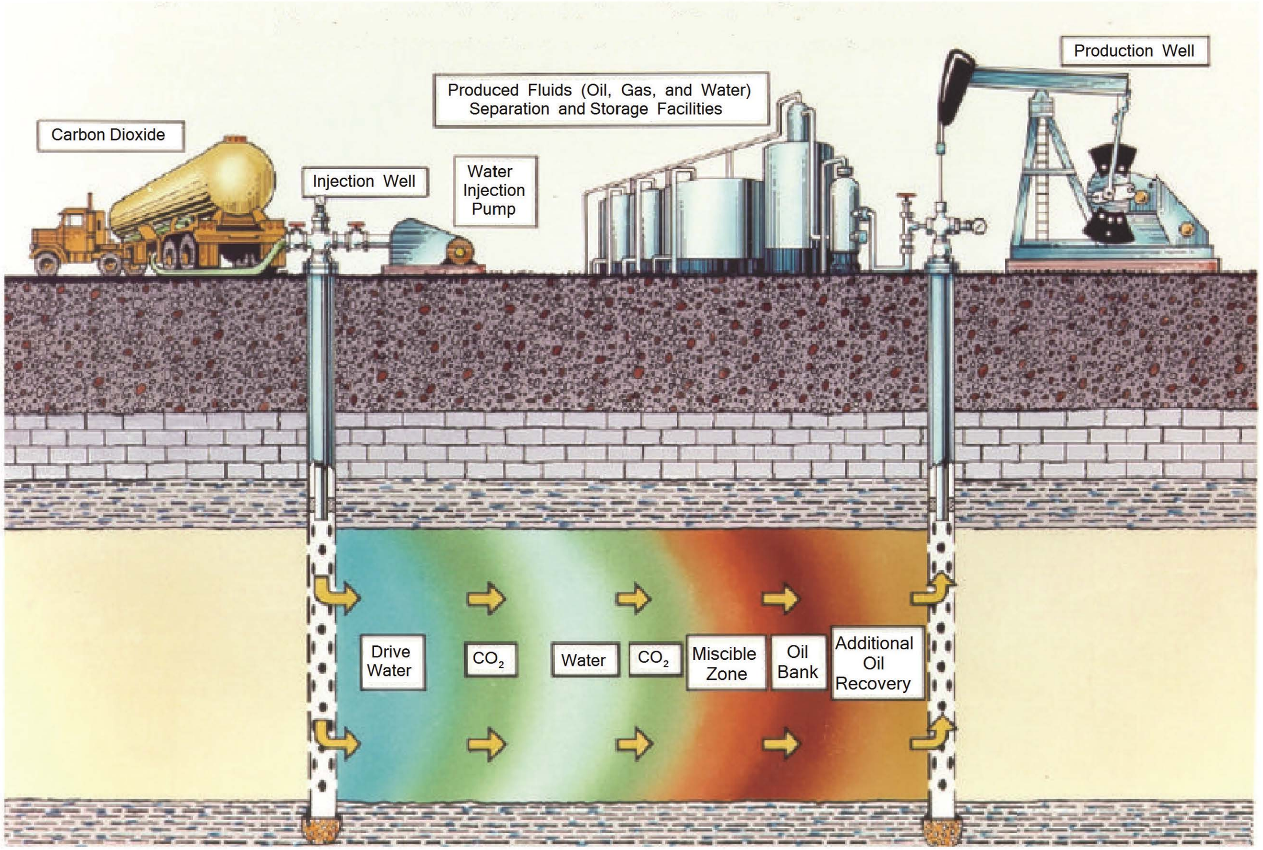

Figure 2. Carbon dioxide flooding.

(Modified from An Overview Study of Enhanced Oil Recovery, Clyde O. Fay, December 1982) upon the reservoir. A checkerboard pattern is often used, where black squares might represent injection wells and red squares represent producers (Figure 3). The CO_2 produced can be extracted from the recovered crude and reinjected.

<u>Efficiency Factors</u>

There are several critical "factors" for an efficient CO_2 flood. A loss of displacement efficiency will result if sufficient pressure for complete mixing of CO_2 and oil is not maintained (11). The minimum pressure required for miscibility is directly proportional to the reservoir temperature (7). If the pressure is too low for the CO_2 to mix with the oil, the CO_2 acts only as a repressurizing gas for the oil field. This comparatively rare method of enhanced oil recovery is known as immiscible carbon dioxide flooding and is practiced only on oil fields that have not yet been waterflooded (3). Water can be injected into the reservoir in order to raise the pressure up to the minimum miscibility pressure (3). Since most oil fields in the United States have been waterflooded, miscible CO_2 flooding is the more common method.

The pressure at which CO_2 and oil mix is affected by reservoir temperature, oil composition, and the purity of CO_2 (4). Impurities in the injected CO_2 such as methane or nitrogen will increase the pressure needed for complete mixing of the CO_2 and oil (4). Most CO_2 that is used for EOR comes from nearby natural deposits. These natural CO_2 reserves are likely to have some impurities, so the chemical composition of injection gas must be checked.

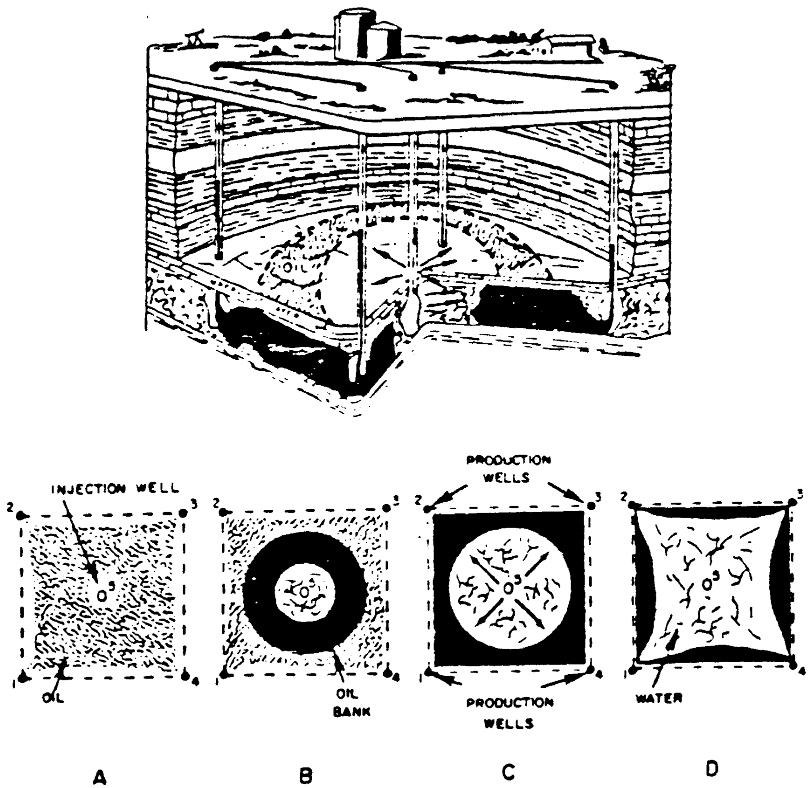

Figure 3. Schematic diagram of an oil reservoir and the displacement of oil from an injection well to surrounding production wells.

(Modified from An Overview Study of Enhanced Oil Recovery, Clyde O. Fay, December 1982)

In addition, any CO_2 that is extracted from the oil which is being produced must be "cleaned" before reinjection.

Water is sometimes injected along with the CO_2 in order to improve sweep efficiency and lessen the cost of recovery. Many CO_2 projects use an alternating injection method where CO_2 is injected for a period of weeks followed by injection of water for the same period. However, each field is different, sothere is not only one specific procedure for every CO_2 flood. Slight differences in reservoir or oil characteristics require slight modifications of enhanced recovery procedures.

Gravity segregation is a problem that can reduce efficiency of the CO_2 miscible flooding method. When water is injected into the reservoir with CO_2, the density contrast between the water and CO_2 may cause the CO_2 to flow to the upper part of the reservoir, greatly reducing recovery. This and other problems are being studied in the laboratory and in the field so that they may be understood and corrected.

RESEARCH AND DEVELOPMENT OF THE CO_2 FLOODING METHOD

Because of the great potential to increase oil recovery at many oil fields in the United States, a great deal of laboratory research and field tests are being conducted so that the CO_2 miscible flooding method can be applied with greater efficiency. The Department of Energy has granted approximately &750,000 to the New Mexico Institute of Mining andTechnology to study the effectiveness of chemical foaming agents as a mobility control during a CO_2flood (7).

Mobility Control

During the early stages of development of CO_2 miscible flooding, control over the CO_2 once injected, was lost. As a result, major problems arose, such as fingering of the CO_2 and premature breakthrough at producing wells. When this happened, the well where the breakthrough occured had to be capped or converted into an injector, both of which resulted in reduced recovery of oil. In laboratory studies at the New Mexico Institute of Mining and Technology, John P. Heller and Joseph J. Taber observed that foam-like dispersions of dense CO_2 in a surfactant aqueous solution reduced fingering of CO_2 (7). A field test at Rock Creek Oil field, Roane County, West Virginia is currently underway.

Optimal CO_2 Volume

Additional research is being conducted by Joseph S. Osoba at Texas A & M University to determine oil recoveries for various degrees of miscibility. The results showed that optimal displacement efficiency can be achieved with a 30 percent hydrocarbon pore volume CO_2 slug (7).

CO_2 Field Tests

A CO_2 minitest was conducted at the Little Knife Field, Billings County, North Dakota (3). A great deal of information and knowledge was gained as a result of this CO_2 field test. The CO_2 flood was performed on a dolomitized carbonate reservoir in the Mission Canyon formation. The producing horizon has an average thickness of 35 feet and is at a depth of 9,700 to 9,900 feet. This reservoir has been undergoing primary recovery by fluid expansion since its discovery in January, 1977.

The CO_2 flood was performed using an alternating water and CO_2 injection method. This was done as a mobility control to prevent fingering of the CO_2. Four observation wells surrounded a single injection well and showed that a straight waterflood displaced 37 percent of the original oil in place at the beginning of the project, compared to a 50 percent displacement of oil by a CO_2 flood. This means that the CO_2 flood gave an 8 percent incremental oil recovery over the straight waterflood. This mini-test confirmed lab results and indicated that the CO_2 miscible flooding method of oil recovery has potential for commercialization in a carbonate reservoir that has not been waterflooded and has a high remaining oil saturation (3).

One of the most complete descriptions of a CO_2 flood pilot project is an article in the March, 1985 volume of the Journal of Petroleum Technology entitled "Development and Status of the Maljamar CO_2 Pilot" by K.R. Pittaway, J.W. Hoover and L.B. Deckert. The CO_2 at Maljamar was injected into the Permian age carbonate rock formations of the Maljamar Cooperative Agreement (MCA) Unit. The major objective of this pilot was to provide a basis for the economics of a commercial-scale CO_2 flood for the MCA Unit (15). Maljamar field is located in Lea County, New Mexico. Several oil reservoirs exist within the Maljamar field, however, only the Grayburg-San Andres reservoir was developed and studied for a CO_2 flood.

Since its discovery in 1928, this reservoir has been injected with gas and water in order to recover additional oil. Gas injection began in 1942 and was phased out gradually after waterflooding began in 1963. In 1972, oil production from the waterflood peaked and began to decline. Production curve analysis indicated that a production limit would be reached around 1996. Cumulative oil production after waterflooding is estimated to be 63 million barrels, however, this will be only 30 percent of the original oil in place. The other 60 percent, or approximately 120 million barrels, remain in the reservoir after waterflooding as a target for the CO_2 miscible flooding method.

Because of the economic risks involved with a commercial scale project, a 5-acre pilot project was developed at a nearly-watered out section of the Grayburg-San Andres reservoir. Four producing wells and radioactive tracers were used to determine flow rates and to detect the oil and CO_2 bank as it moved out away from the injection well toward producing wells. Corrosion of producing wells was a major problem with this pilot project resulting in downtime and decreased production. Although production results aren't available yet, this field test is providing valuable information about CO_2 flood operation which is needed to estimate economics of commercial scale CO_2 flooding projects.

TARGET RESERVOIRS

Research and field tests have shown that the CO_2 miscible flooding method is applicable to carbonate and sandstone reservoirs at a depth of 2300 feet or greater. The pressure in shallower reservoirs is not great enough to cause the CO_2 and oil to mix. In deeper reservoirs, where the pressure is even greater, the CO_2 miscible flooding method could recover very viscous oils. Generally, reservoirs in which oil viscosity is greater than 10 centipoise are not considered for a CO_2 flood (4). Other reservoir screening criteria include an absence of natural factures, minor gas caps, and minor bottom water drive. If the temperature of the reservoir is above 250° F, the CO_2 miscible flooding method will not be used because the pressure required for miscibility would be too great. If a reservoir passes this general screening test, a small scale field test or pilot is usually conducted.

CO_2 SUPPLY

The source of CO_2 is another screening factor for this EOR method. Before a CO_2 flood project begins, a CO_2 source must be indentified and a method of CO_2 transport, from the source to the oil recovery site must be planned. Sources of CO_2 include natural deposits, coal gasification plants, chemical and fertilizer plants, and power plant stack gas (4). Natural gas deposits, the most common CO_2 source for EOR, contain the large volume of CO_2 needed for EOR operations. The other sources are relatively limited and expensive however they can be used as a source of CO_2 for EOR. For example, Amerada Hess Corporation is planning a CO_2 miscible flooding project in the Williston basin of North Dakota and Montana. The source of CO_2 is anticipated to be the Great Plains coal gasification plant near Beulah, North Dakota (1).

Often the CO_2 source is many miles away from the oil recovery site. Transportation of CO_2 can be accomplished by pipeline, refrigerated truck, or by tank car. In the Permian Basin, where many CO_2 miscible flooding projects are operated or planned, pipelines carry the large volume of CO_2 needed in the most economical way. In other areas, where the required volume of CO_2 isn't as large, transportation by truck or tank car can be used.

CURRENT CO_2 PROJECTS

Several major oil companies, including Amoco, Amerada, Exxon, and Conoco, have begun CO_2 flood operations in the Permian Basin and other areas. Figure 4 shows the oil company and field where CO_2 flood projects are operating or planned. The Permian Basin is one area where CO_2 miscible flooding has the greatest potential. Many large carbonate reservoirs that have a high saturation of high gravity (light) oil are located in the Permian Basin. The amount of oil recoverable in the Permian Basin by CO_2 flooding is estimated at 10 billion barrels (12). And if the price of crude oil goes up, this figure could get even higher.

One of the reasons for the great potential for the CO_2 flood in the Permian Basin is the source of CO_2. Nearby, in

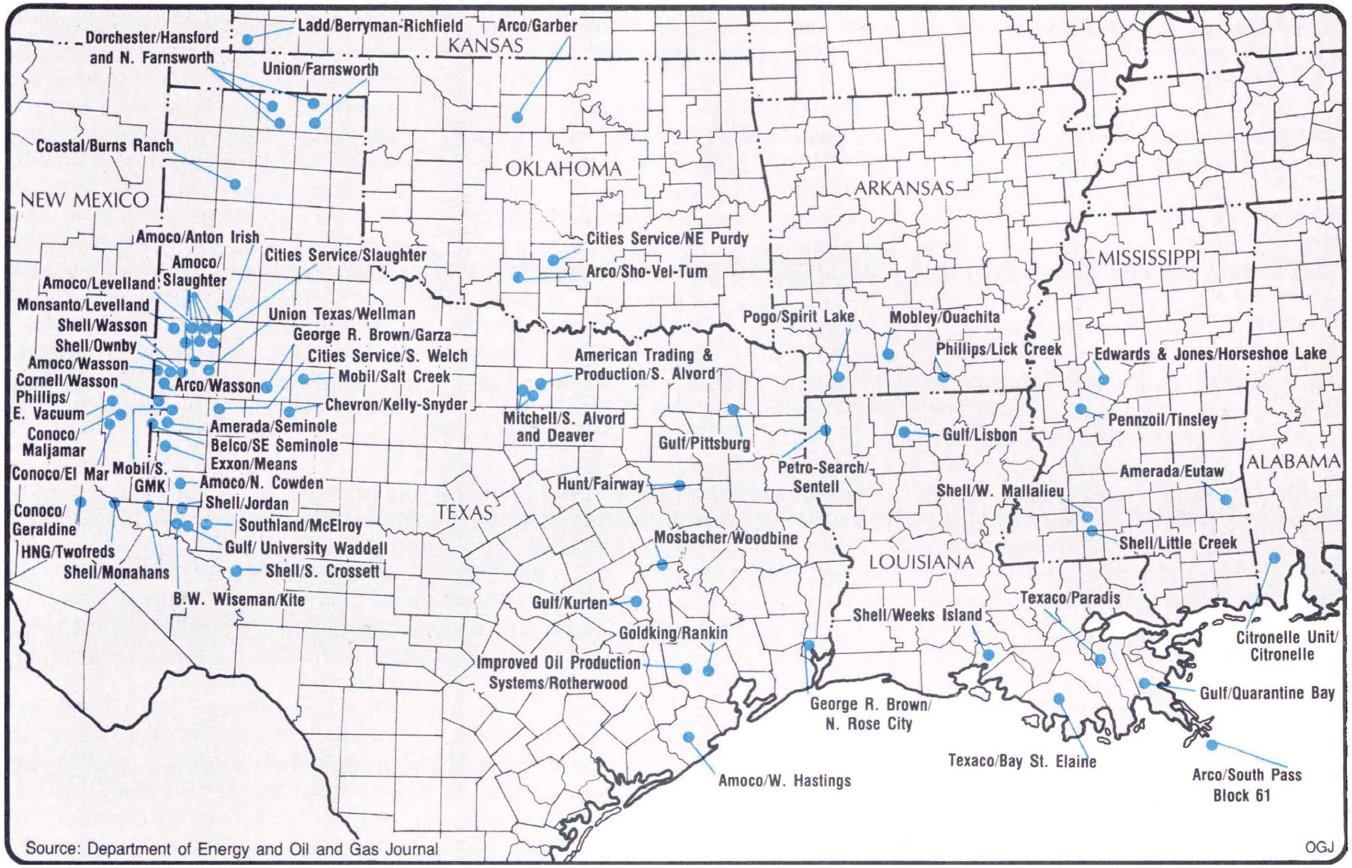

Figure 4. Where the bulk of U.S. carbon dioxide flooding projects is underway or planned.

(Taken from Oil & Gas Journal, January 3, 1983)

Colorado, several large natural deposits of CO_2 are contained within the ground associated with oil reservoirs. Several oil companies have begun to construct pipelines to transport CO_2 relatively cheaply from these natural deposits in Colorado to West Texas and eastern New Mexico (Figure 5). One such company is Amerada Hess.

Amerada Hess Corporation has joined forces with Exxon Company, U.S.A. and ARCO Oil and Gas Company in order to construct a pipeline that will carry large amounts of CO_2 from Southeast Colorado to West Texas for use in several CO_2 flood projects. Proposed project reservoirs include the Seminole San Andres Unit and theWillard San Andres Unit, both in the Seminole field, the Denver Unit in Wasson field, and the Cornell Unit, also in Wasson field.

Amerada Hess Corp. Plans to inject a total of more than one trillion cubic feet of CO_2 into the 17,221 acre Seminole San Andres Unit in Gaines County, Texas. This particular reservoir had an estimated 1.15 billion barrels of original oil in place. 268 million barrels (23 percent) were recovered by primary methods. Another 202 million (18 percent) were recovered by secondary methods. CO_2 miscible flooding is expected to result in recovery of an additional 175 million barrels of oil (15 percent) (12).

As mentioned earlier, Amerada Hess Corporation plans to construct a pipeline to transport CO_2 from a coal gasification plant near Beulah, North Dakota to EOR projects in the Williston

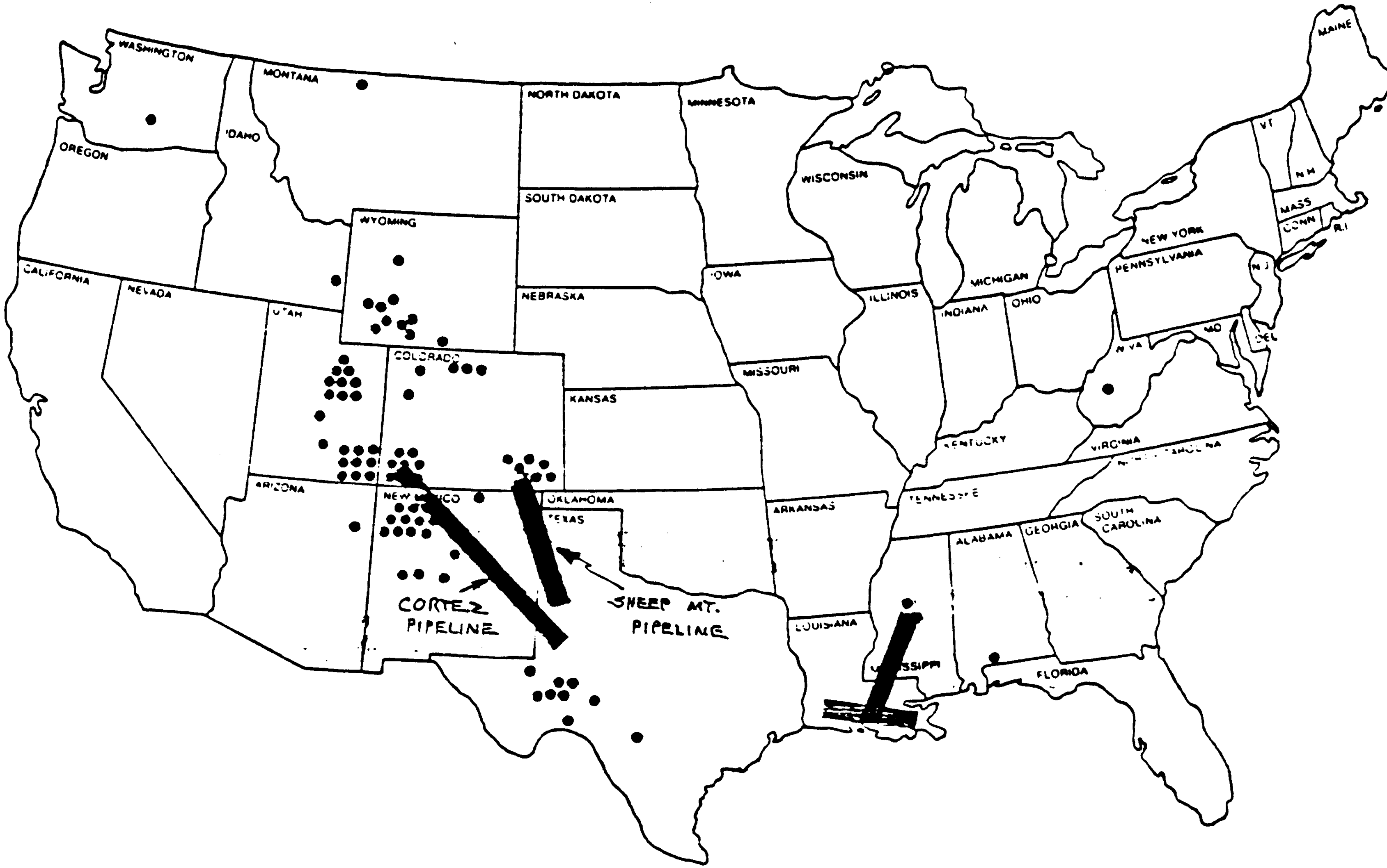

Figure 5. Black dots represent natural gas deposits with a high concentration of CO_2. Major CO_2 pipelines are also shown. (Modified from Enhanced Oil Recovery, National Petroleum Council, December 1976)

basin of North Dakota and Montana (Figure 6). Not much information is available on this project because so far it is just proposed (1).

Another CO_2 flood has been proposed for the Rangely field, Rio Blanco, Colorado. This project is expected to produce 106 million barrels of oil due to CO_2 injection which makes it the biggest outside of the Permian Basin. Exxon hopes to supply the CO_2 to Chevron, owners of the Rangely field, from natural deposits in the La Barge Platform of Southwest Wyoming in 1986 (13). Exxon plans to announce four more company operated CO_2 floods in the Permian Basin by the end of 1985. Exxon expects to recover as much as 7 million barrels of additional oil in the Permian Basin by the CO_2 flooding method (10).

Texaco is also planning EOR projects using CO_2, however their technique is slightly different. They plan to use the "huff puff" method of CO_2 injection at two oil fields in Texas. The huff puff method involves injecting CO_2 into each well. Then, after a shut in period, all wells will be converted into producing wells. Texaco plans to vary shut in periods in order to determine the affect of time on recovery. With this method, Texaco hopes to recover 23,300 barrels from Magnet Withers field, also in Wharton County, Texas (14).

Other major oil companies that plan CO_2 floods include Gulf, Shell, and Mobil.

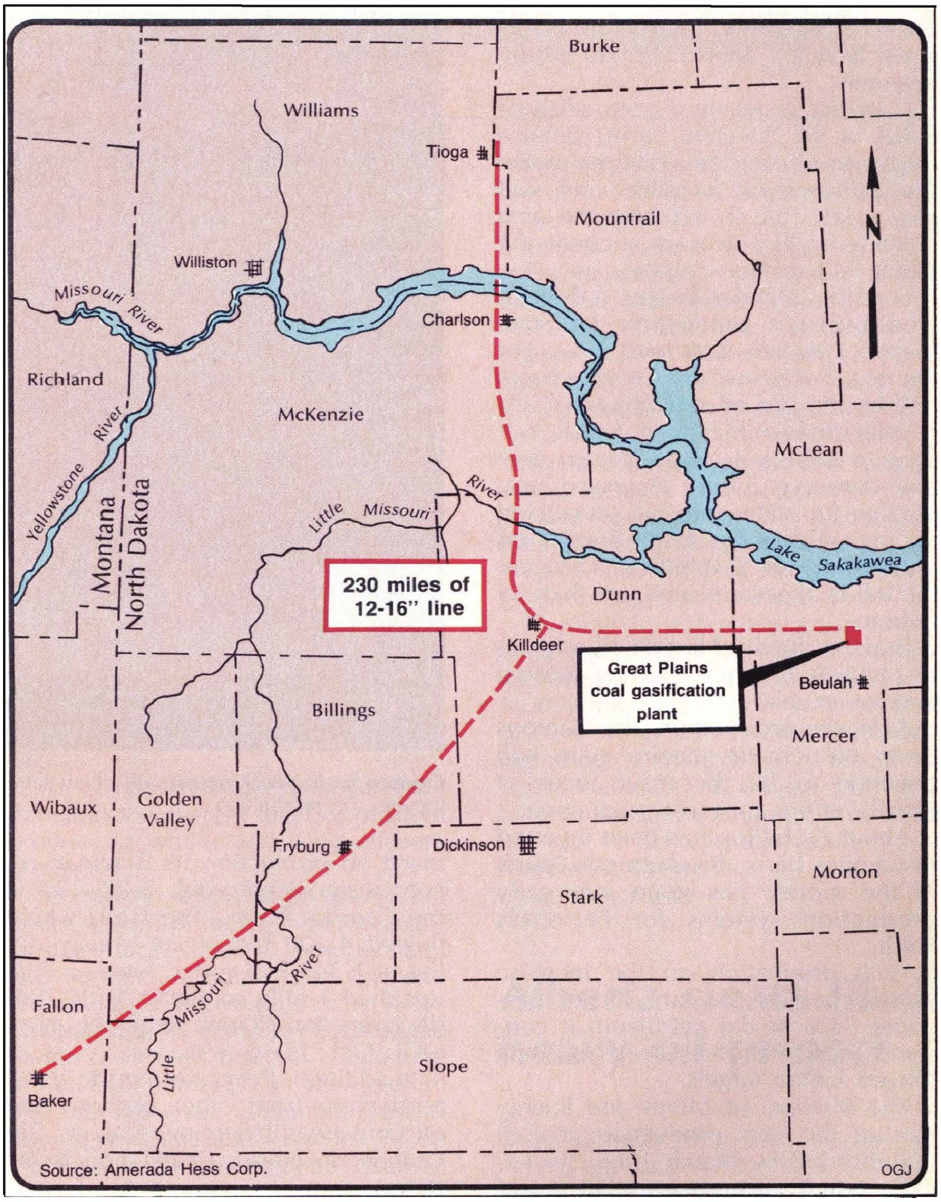

Figure 6. CO_2 pipeline proposed by Amerada Hess. (Taken from Oil & Gas Journal, December 3, 1984)

CONCLUSION

Recovery of oil from reservoirs has evolved from a passive activity into an aggressive engineering challenge. In 1977, half of the U.S. oil production was due to waterflooding (4). As these waterfloods reach a productive limit, EOR projects will take their place. Several EOR techniques exist now and more will develop in the years to come. The carbon dioxide flooding method of enhanced oil recovery has great potential to increase domestic oil supply in certan regions of the U.S. where the conditions are right. The source of CO_2 is just one of these restrictive conditions. Nearby, large natural deposits of CO_2 create great potential for additional oil recovery by the CO_2 flooding method in the Permian Basin.

The Carbon Dioxide flooding method of enhanced oil recovery isn't applicable to all reservoirs. Certain reservoir conditions have to be met in order for a CO_2 flood to be feasible and economic. Where those conditions are met, the CO_2 flooding method has great potential to increase the domestic oil supply for the United States.

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